The Importance of Iron Ores in Direct Reduction

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1. Historic approaches in the development of pellets for Direct Reduction.

HYL has been actively involved in the direct reduction (DR) field since the 1950's. Experiences gathered from industrial installations together with an active R&D organization, support a deep knowledge on the behavior of different iron ores in the DR field.

The quality specifications for an iron ore to be used in DR plants include the chemical, physical and metallurgical properties. Historically, the first specifications were taken from models similar to those already developed for the blast furnace. Once DR processes accumulated enough experience, the tests, conditions and evaluations were adjusted in order to better represent what actually takes place in a DR process.

Regarding the specifications for the chemical composition of the ore, which appeared several years before the metallurgical properties evaluation, the economy of the overall steelmaking process was taken into consideration, as well as the influence by the presence of some particular elements on the behavior of pellets while being reduced. Reducibility, swelling, shrinking, size degradation and sticking were the most important phenomena, affected by the chemical composition of the ore. From the experiences in the operation of DR plants, some requirements about the concentration of particular components were established to assure an optimum behavior.

When specific methods were developed for measuring the metallurgical properties of iron ores, several studies were conducted to correlate the iron ore composition with the metallurgical properties. According to these evaluations, the iron ore chemical specification has been continuously adjusted.

1.1. The steelmaking cost.

In steelmaking via DR - Electric Arc Furnace (EAF), when pellets are used as raw material, there are two possibilities to adjust the chemical analysis of the steel produced.

One possibility is through concentration and pelletizing of iron ore, to eliminate as much as possible excess of gangue, to increase the total iron content. The other possibility is to adjust the composition in the EAF or in the ladle after the DRI is melted.

In this regard, the economy of the overall steelmaking process (DR-EAF) is an important condition for the adjustment of the ore chemical composition during the pelletizing process.

Some elements commonly present in the ore, when exceeding certain limits, could increase the steel production costs. For such case, it is necessary to avoid the presence of those elements in the EAF, and in consequence, to be eliminated or at least minimized during pelletizing process.

This is the case of sulphur, phosphorous and all those elements that are considered residuals in the liquid steel, such as tin, copper, chrome, etc. Currently, all pellet producers are well aware of this situation and the content of these elements is properly adjusted. The maximum concentration of them is considered and agreed in the quality compromises with the customers.

The pellet basicity in its binary ($B_2=CaO/SiO_2$) or quaternary ($B_4=[CaO+MgO]/[SiO_2+Al_2O_3]$) forms, is a parameter that in some cases is convenient to be adjusted in the pelletizing process, while in others it is better to do it in the EAF. Since the refractory lining of the EAF is based on basic elements (MgO), it is well accepted that a basicity of 0.9 to 1.1 optimizes the steelmaking costs.

This was the basis for original criteria of HYL as recommendation for characteristics of iron ore pellets.

1.2. Development of chemical and physical properties.
Since Hylsa started operation of its pelletizing plant in 1970, a continuous process has been followed to optimize the pellet quality. The experience from the operation of Hylsa DR plants has provided valuable data for this optimization process.

A proper selection of the binder in the pelletizing process allows improving the pellet physical properties, to minimize the fines generation during handling, transportation and charge to the reduction reactors. Bentonite, limestone and other additives were tried until the pellets achieved the required quality level regarding physical properties, as indicated by the tumbler index, impact index, cold compression strength, porosity and size distribution.

With additional magnetic concentration step in the pelletizing plant, pellets of different chemical compositions were fed to the reduction reactors but no major changes were made to the specifications.

1.3. Improvements from DR plants operating experience.
The operation of HYL DR plants worldwide has provided the opportunity to test and evaluate different pellets and ores available in the market. Some of these experiences are related to:

TiO_2 content.
The presence of high TiO_2, from test based on pellet samples made from titaniferous sands, influenced the material swelling behavior, which was reflected in pellets deformation, causing particles agglomeration, clusters formation and decreasing the bed permeability to a level where gas irrigation was very poor. From this experience, the TiO_2 content was restricted in the iron ore specifications.

Na_2O+K_2O content.
The content of alkaline compounds (Na_2O+K_2O) was also restricted. For this test, seawater was used in the pelletizing process. The results showed a correlation between a high content of these compounds and a high tendency to clusters formation. These elements form low melting point compounds in the pellet surface.

Fe++ content.
The Fe++ content is a parameter that clearly shows the oxidation pellets degree. In case a pellet is not homogeneously oxidized, it is expected that its core remains as magnetite and consequently the reducibility and mechanical resistance are adversely affected.

2. Iron ores' quality specifications of relevant importance for DR.

The raw materials most suitable for direct reduction-steelmaking are selected according to the following criteria:

- Chemical characteristics.
- Physical and metallurgical properties.
- Overall economics of both direct reduction and steelmaking.

2.1. Chemical characteristics

Besides some particular restrictions on TiO_2 and alkaline compounds, for the HYL DR process, there are not practical limitations regarding the chemical composition of the iron ore.

As mentioned above, it should be stressed that an adequate selection of iron ores shall consider the overall economics of the direct reduction and steelmaking processes. Although a low chemical quality of the ore will not affect adversely the reduction process, the energy needed for DRI melting in the EAF is definitely influenced by the gangue content, basicity, and metallization and carbon levels.

Although there are some restrictions on residuals and ore basicity in EAF operations, it should be underlined that for the HYL process neither residuals nor ore basicity is a limitation at any level.

2.2. Physical and metallurgical properties

The most important iron ores properties, which affect the performance of the HYL DR plant, can be summarized as follows:

- Particle size distribution

  The most suitable particle size of iron ores to be processed in the HYL reactor is in the range of +6 mm and -16 mm.

  a) Large particles present higher resistance for reduction.
  b) Small particles tend to increase the pressure-drop (ΔP).

- Reducibility

  The reducibility of the iron ores depends mainly on:
  a) Particle ore porosity.
  b) Particle size.
  c) Chemical composition of the phases present in the ore.

A low reducibility would result in low metallization of the product if no provisions were taken in the definition of process parameters.

- Sticking tendency

  The sticking problems in DR shafts are associated to the following phenomena:

  a) The consolidation of solid material, due to the development of ferrostatic pressures between particles or particles with the wall, or by swelling which deforms the particles and increases the contact area between them.
  b) The tendency to form bonds between the particles.

  Consequences of sticking can vary from the appearance of small clusters in the DRI discharge to the stoppage of the solids flow.

- Fines generation

  Fines generation is the effect of the following causes:

  a) The strength of the ore (and the associated DRI) to physical degradation.
  b) The particle internal stability through the reduction process.
  c) Crystallization water or carbonates expelled out of the particle (as steam and CO_2) while being heated.
  d) The composition of the reducing gases. Typically, reduction with hydrogen-rich gases shows a tendency to lower fines generation.

  Fines generation may have several harmful effects:

  - Heterogeneous quality of the product.
  - High-pressure drop.
  - High amount of solids carried out of the reactor by the gas stream.
  - Gases flow misdistribution.

  In general, lump ores usually generate more fines than pelletized ores. The ceramic net formed by the gangue in the pellet is better controlled and achieved in the pelletizing process than the natural structure of the lump ore which, in most cases, is more erratic and fragile.

  As the material is first handled and then reduced, the pellets behave stronger to degradation than the lump ores. It is important to mention that some lump ores will behave strong to physical degradation but fragile during either, drying or the crystallographic rearrangement inside the DR reactor. The opposite may also occur.

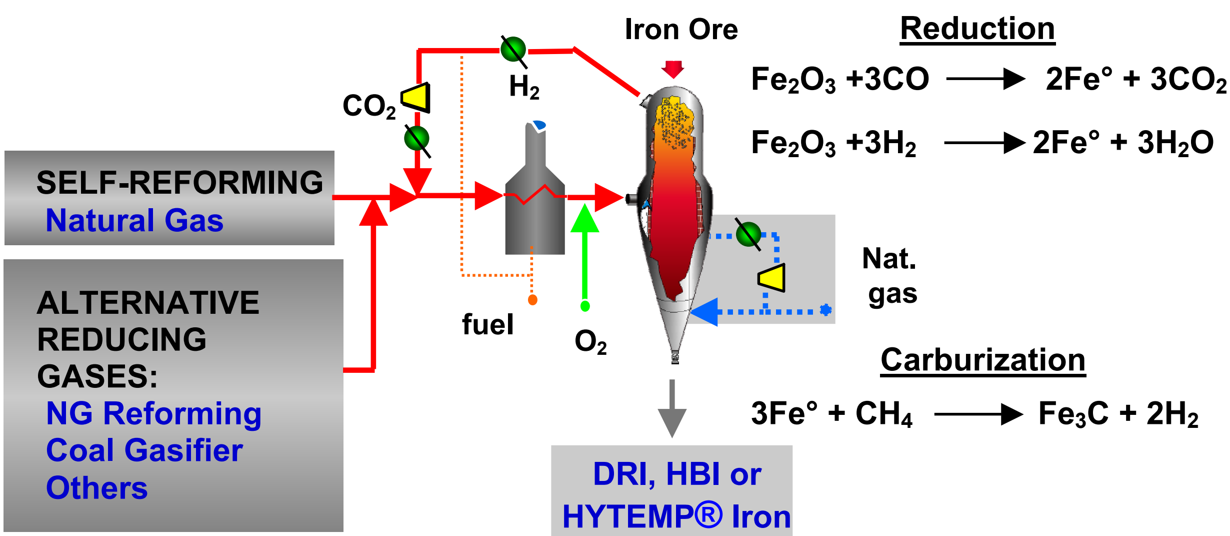
  Other difference between pellets and lump ores is related to crystallization water and some carbonates contained in the natural structure of the particles. Pellets never have crystallization water. In some lump ores, these compounds are present and become violently vaporized or gasified during drying and reducing stages of the process inside the reactor thus, producing severe decrepitating of the particles and increasing significantly the fines generation.

3. Flexibility of the HYL DR process in adjusting operating parameters to operate with iron ores of different behavior.

The HYL process concept is presented in Fig. 1. The process is designed for the direct reduction of iron ores (in pellet or in lump form) by the use of reducing gases in a solid-gas moving bed reactor. Oxygen is removed from the iron ores by chemical reactions based on hydrogen (H_2) and carbon monoxide (CO), for the production of highly metallized Direct Reduced Iron (DRI). In the reduction reactor, iron carbide (Fe_3C) is also formed by the combination of carbon with metallic iron from the reduced product.

Depending on the scheme configuration (i.e. Reformer-less or ZR, use of reformed gas or other alternate reducing gases), the operating conditions in the HYL process are based on a reducing gas composition rich in hydrogen (70%-87%), elevated pressure (> 5.5 kg/cm^2) and high reduction temperature (> 920°C).

Figure 1
HYL Process Configurations



DRI: for internal use or regional export

HBI: as merchant product for export

HYTEMP® iron: hot DRI, transported pneumatically to the EAF

The main process parameters considered for design and operation of the HYL plant are:

- Specific reducing gas flow rate entering the reactor.
- Inlet reducing gas temperature.

- Operating pressure.
- Specific cooling gas flow rate (for cold DRI discharge).
- Adjustment of reducing gas composition.

Normally, definition of these process parameters is obtained by correlation between the laboratory determinations of the ores metallurgic behavior and the performance of the particular ore in the pilot/industrial plant. In many cases, certain ores behave in the laboratory in an equal or very similar way to others already tested in pilot/industrial facilities. For these cases there is no requirement for testing in order to fix the corresponding process parameters. However, pilot plant tests are recommended for detail adjustments of the process operating conditions.

- Chemical analysis

  Iron ores with common impurities such as sulphur and phosphorous, which can be present in some ores in relatively high concentration, can be used without any technical limitation in HYL plants. Moreover, due to inherent process scheme characteristics, most of the sulphur of the iron ore is converted to H_2S in the reduction reactor and eliminated from the process in subsequent separation steps.

- Reducibility

  In provision to possible low reducibility, a minimum residence time shall be considered for reactor design.

  Residence time: $\tau = V_R / Fs$ **(h)**

  where: V_R = Vol. of reactor reduction section (m^3)

  F_S = Solids flow rate (m^3/h)

  Additionally, process parameters, such as, reducing gas composition –including adequate selection of process scheme-, specific reducing gas to reactor and/or reducing gas temperature can be adjusted to process iron ores with this particular characteristic.

- Sticking tendency

  To prevent cluster formation, the following provisions can be taken in the HYL reactor operation and design:

  - To blend the ores in proper mixtures, so the affinity of the individual particles to form bonds is reduced.
  - For very high sticking ores, an alternate and very effective procedure to decrease significantly the sticking tendency is to coat the ore load with a leach of materials mainly composed by MgO and CaO (like cement, or some other agents), which block the particle affinity by inhibiting the interparticle bond formation during the reduction process.

- <u>Fines generation</u>
  In connection to the potential harmful effects due to fines generation, described above, the HYL process has the advantageous position of the high operating pressure and a proper reactor design.

  The advantage of high operating pressure is of most importance and an implicit characteristic of the HYL DR process in terms of reactor productivity, low gas velocity and fluidization.

4. Recent operational experience in operation and development of iron ores. Case history: successful development of Lebedinsky pellets for DR.

The Lebedinsky works located in Gubkin, Russia comprise mining, concentration and pelletizing facilities. An HBI plant, based on the HYL process, was installed to produce 0.9 Mio tpy of HBI.

The original pellets for the DR plant are characterized by particular properties, such as: high reducibility, very high sticking tendency and gangue with relatively high SiO_2.

During the start of operations the behavior of the material in the reactor was reflected in uneven and erratic solids flow. The sole adjustment of process parameters and pellets coating was not enough to achieve a continuous operation with the required product quality.

As result of intensive analysis and R&D program, it was clear that the pellets presented an unusual high internal friction angle and plasticity behavior, which were the main reasons of the abnormal solids flow pattern.

From the pelletizing side, the following actions were taken: modification of the heating curve and adjustment of the gangue through bauxite incorporation.
From the process side, implementation of proper cement coating, together with adequate reduction temperature (about 900°C) and specific reducing gas adjustment with highly reductants'-rich gases (H_2+CO >87%; CO_2<3%).

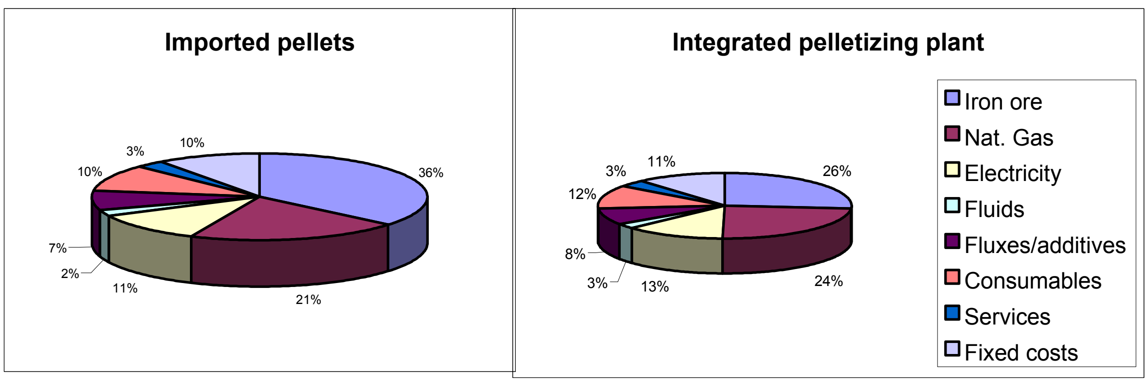
Combination of actions in both, pelletizing and HYL DR process parameters made possible the elimination of solids flow problems for a smooth and continuous plant operation, reaching design production and a high HBI quality, with metallization >94%, carbon below 1% and density >5 g/cm^2.

5. Economical aspects related to iron ores to be considered in the implementation of steelmaking projects.

Elaboration of economical analysis for integrated projects oriented to the production of steel, shall consider the benefits of integrated pelletizing facilities in the production cost. Final impact of these benefits in the overall production cost will depend on the pelletizing capacity associated with the DR and mill production, related to additional investment cost. An important limitation for the potential incorporation of the pellet plant is precisely its minimum feasible capacity, linked to the requirements of the DR production.

Taking as an example an integrated facility for the production of slabs, with prevailing costs in the Gulf Coast, the imported iron ore pellets impact is about 36% of total slab process cost. The analysis is based on the use of 100% pellets. As presented in Fig. 2, the corresponding cost factor of the iron ore can be reduced to about 26%, when incorporating its own pelletizing facility. This is reflected in approximately $23 US/t slab (process cost), which has to be compared to additional required investment cost of the pellet plant.

Figure 2
Use of commercial pellets vs. integrated pelletizing-DR facilities
Slabs process cost



6. Conclusions.

The economic production of DRI is mostly influenced by the cost of iron ore, as pellet, lump ore, or fines, depending on the capabilities of each direct reduction process. Special emphasis has to be taken in proper selection of iron ores by considering not only the availability and market price but also the economy of the overall steelmaking process and the particular characteristics of the material, which may drastically influence in the performance and operating costs of the process.

The HYL DR technology while being evolved from fixed-bed to the optimized Self-reforming (ZR) scheme through more than 44 years of R&D and the experience of industrial operations, keeps high process flexibility to be adjusted for the use of different raw materials. Additionally, the operation of own pelletizing facilities, R&D installations, together with the knowledge and experience obtained from the operation of different ores, may provide important information for prediction and testing analysis of iron ores to be processed in DR plants.